Renewable and Sustainable Energy Reviews 35 (2014) 304–310

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Optimal load distribution model of microgrid in the smart grid environment

Kaile Zhou*, Shanlin Yang, Zhiqiang Chen, Shuai Ding

School of Management, Hefei University of Technology, Hefei 230009, China

ARTICLE INFO

Article history:
Received 27 September 2013
Received in revised form
18 March 2014
Accepted 7 April 2014
Available online 25 April 2014

Keywords:
Microgrid
Smart grid
Distributed generation
Optimal load distribution
Optimization model

ABSTRACT

In the smart grid environment, the flexible and diverse distributed generation (DG) and microgrid (MG) are attracting considerable attention. There are many key management and optimization issues involved in smart grid. As an important part of smart grid optimizations, the optimal load distribution of MG contributes to the efficient operation of MG in the smart grid environment. However, traditional optimal load distribution models of large-scale power generation systems are not fully applicable to MG for their distinct characteristics. In this paper, we first introduce the MG in smart grid and analyze its characteristics. Then, we present a review of the optimal load distribution models of MG in the smart grid environment, and point out the deficiencies of the existing models. Finally, a comprehensive optimal load distribution model of MG both in objective functions and constraints is established and discussed.

Contents

1. Introduction

With the rapid development of power generation technologies and the increasing demand for electricity, large-scale centralized power generation systems were widely implemented, in which thermal power is the major power generation method. However,

* Corresponding author.
E-mail addresses: kailezhou@gmail.com, zhoukaile@mail.hfut.edu.cn (K. Zhou).

http://dx.doi.org/10.1016/j.rser.2014.04.028
1364-0321/

the disadvantages of large-scale centralized thermal power generation, such as disadvantages in the aspects of economic efficiency, environmental protection, security and reliability, and control agility, were gradually emerging. People began to re-evaluate the large-scale centralized power generation methods, and the idea of small-scale distributed generation was presented [1]. After the late 1990s, increasing research efforts have focused on the distributed generation (DG) and its economic benefits [2–5]. DG, also known as dispersed generation or distributed energy supply, is a new energy production and supply model [6–8]. In DG, relatively small power generation units are arranged near the user load sites. Therefore, compared with the large-scale centralized power generation, the main advantages of DG are its dispersion in locations and flexibility in power supply. In addition, DG can also improve the reliability of power supply system when collaborating with large-scale power generation systems [9]. However, DG also has some disadvantages. The main power grid always employs methods like restriction and isolation to reduce the impact from DG. With the development of smart grid, the concept of microgrid (MG) [10–12] was proposed in order to coordinate the contradictions between DG and the main power grid. MG is an important power generation mode in smart grid [13–15].

Currently, MG is primarily in the experimental research stage [16–18]. There are still many obstacles in terms of technology, control and management that needs to be overcome before MG can be widely applied [19–21]. The economic optimization of MG is one of the key management issues which can affect its operating efficiency and user acceptance [22–24]. Three aspects of MG economics were summarized in [25]. Solar power, wind power and other renewable energy power generation methods are widely adopted in MG, which makes its environmental benefits apparent [26]. Also, power generated in MG can be supplied in a safer, more reliable, and more personalized way by means of electricity users division and load classification [27,28]. Currently, there have been some research efforts in the economic optimization of MG [29–32].

The various optimization issues are the key parts of MG economics, such as the location optimization [33–35] and capacity optimization [36–38] of distributed generators in order to determine the location and capacity of each generator. The optimal load distribution is an important optimization problem to support the efficient operation of MG [39]. The optimal load distribution of MG is to achieve multi-objectives, including low operating cost, low emissions, high reliability, high power quality, and low line loss, etc., while meeting various system operating constraints. In this paper, we will review some existing optimal load distribution models of MG, and point out the deficiencies of the existing models. Then a general and comprehensive model of MG optimal load distribution is proposed and discussed.

The remainder of this paper is structured as follows. A brief introduction of smart grid and MG, as well as the optimal load distribution of MG are described in Section 2. Then, the optimization mathematical models of MG optimal load distribution, both single-objective and multi-objective, are reviewed in Section 3. In Section 4, we propose a comprehensive model of MG optimal load distribution, including different objective functions and various constraints. Finally, conclusions are drawn in Section 5.

2. Optimal load distribution of MG in the smart grid environment

2.1. MG in the smart grid

To achieve the goal that the operation of power systems becomes safer, more reliable, more environmentally friendly, more flexible, more controllable, and more cost-effective, the United States and some European countries proposed the concept of "smart grid" [40–42]. Currently, many countries have put smart grid as one of the national strategies, and considerable research work have been carried out [43–45]. Smart grid [46–48] can be generally considered as an intelligent power grid system which integrates the energy flow and information flow by advanced information technology, sensor technology, automatic control technology and scientific management methods, etc.

MG is an important part of smart grid implementation and application. A variety of distributed generators and energy storage devices can assess to the main power grid in the smart grid environment. They can form a "virtual power plant" through the interconnection on all voltage levels by electrical communication systems. Many researchers studied the roles of distributed generators and energy storage devices in smart grid. Zhang [49] described a framework for the operation and control of smart grid with DG and Flexible AC Transmissions (FACTS), and proposed a global coordinated strategy for voltage control. Mohd et al. [50] pointed out that distributed energy storage systems with advanced power electronics can play an important role in power supply systems and lead to many financial benefits. They also studied the topologies, control and flexibility of the main power grid with energy storage systems. Chowdhury et al. [51] studied the operation and control of distributed generators in power islands by simulation, and an appropriate bus controller was designed. They also analyzed the flexibility, safety and power quality of DG. These research efforts mainly focused on the technical and control perspective of DG operation in the smart grid environment.

2.2. The characteristics of MG optimal load distribution

MG is a kind of small power distribution and consumption system, which overcomes the deficiencies of DG in terms of intelligence and flexibility [52]. MG provides power energy for users by modern power techniques, such as fast power electronic switches, advanced converting techniques, efficient new energy sources and various energy storage devices. Many kinds of distributed generators and energy storage devices, including photovoltaic (PV) arrays, wind turbines (WTs), microturbines (MTs), fuel cells (FCs), and energy storage batteries, are widely adopted in MG.

MG is a controllable power system that provides thermal and electricity for users by combining the power generation equipment, energy storage devices, control equipment and load [53]. The basic structure of MG has been presented by the America Consortium for Electric Reliability Technology Solution (CERTS) [54]. MG can operate in both grid-connected mode by collaborating with main power grid and independent isolated mode. As an effective supplement of main power grid, MG has attracted considerable attention in recent years due to its characteristics of low cost, low pollution, high reliability and easy to control.

The optimal load distribution of MG is to achieve multiple goals, including minimizing cost, minimizing pollution emissions, and maximizing reliability, etc., while satisfying various constrains. Fig. 1 shows the basic structure of MG optimal load distribution.

There are many differences between the MG and traditional large-scale thermal power generation. First, power generation of various distributed generators in MG usually follows the maximum power-point tracking mode [55,56], and cannot be controlled through manual scheduling. The output characteristics of these distributed generators of renewable energy power generation are sensitive to the natural conditions, such as the intensity of sunlight and the velocity of wind. Second, the power

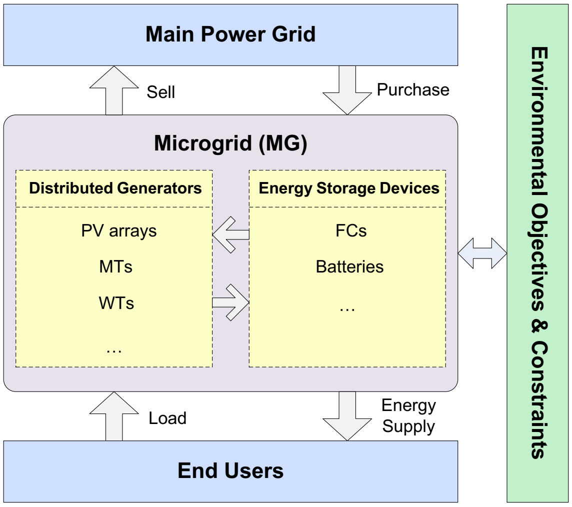

Fig. 1. Basic structure of MG optimal load distribution.

line loss of MG cannot be ignored since the wiring resistance caused by the low voltage is large. Third, the equal incremental principle [57] cannot be directly used for MG, since the power generation characteristics of distributed generators in MG are different from traditional thermal power units. Also, MG should be optimized globally and dynamically according to the system operation, since the power distribution of MG may change a lot when converting between grid-connected mode and isolated mode [58].

Therefore, traditional optimal load distribution models of the large-scale power systems [59–61] cannot be directly applied to MG due to its specific characteristics. New optimal load distribution models for MG need to be developed.

3. Optimal load distribution models of MG

3.1. Single-objective models

The optimal load distribution of MG is actually a multi-objective optimization problem. However, in some existing research work, the multi-objective optimal load distribution models of MG were always simplified to single-objective ones in order to facilitate problem analysis and solving. Chen and Zhu [58] established a single-objective model of MG optimal load distribution. The objective of their model is to minimize the total cost of power generation by optimizing the outputs of distributed generators while meeting the system operation conditions. The objective function of their model is defined as follows:

$$\min F = \min \sum_{t=1}^{T} [\sum_{i=1}^{N} F_i(P_i(t)) + E_{buy}P_{buy}(t) - E_{sell}P_{sell}(t)] \tag{1}$$

where F is system total cost of power generation, T is the total number of periods in scheduling cycle, t is the number of period, N is the total number of power generation units and energy storage devices which can be scheduled within the system, P_i represents the actual power output of unit i,$F(P_i)$ denotes the operating cost of the ith power generation unit or energy storage device, P_{buy} is the electricity bought from the main power grid, P_{sell} is the electricity sold to the main power grid, E_{buy} is the price of bought electricity, and E_{sell} is the price of sold electricity.

There are four constraints in this optimization model, including the operation constraints of power generation units, charge–discharge and capacity constraints of energy storage devices, and power balance constraints. The total operating cost in this model includes fuel cost, maintenance cost, start-up cost, and trading cost and income with main power grid, but does not include the factor of fuel consumption rate. Moreover, the objectives of pollution emissions, system reliability, power quality, and operation efficiency were not considered in the model. Also, the time and quantity constraints of start-stop were not included as well. Therefore, the simulation results of this model may not be so accurate.

Hernandez-Aramburo et al. [62] pointed out that the most significant difference between MG and large-scale power generation systems is the presence of a local heat demand, which adds another dimension to the optimization problem of MG. They proposed an optimal load distribution model that considered the Combined Heat and Power (CHP) System. The aim of their model was to reduce the fuel consumption rate while meeting the local energy demand (both electrical and thermal). However, the emissions and the maintenance costs were not included in the objective function of their model. Therefore, it is difficult to balance the relationship between cost and emissions when using their model.

Asanol and Bando. [63] and Asano et al. [64] also studied the optimal load distribution of MG considering CHP system. The objective function of the mathematical model proposed in [63] includes operating cost, gas cost, electricity bought cost and start-up cost of gas engine. The objective function proposed in [64] takes more costs into consideration, including gas costs, transaction costs with main power grid, the contract demand cost from the main power grid, operation and maintenance costs, start-up costs and the original investment costs. The constraints of this model include power supply and demand balance, charge–discharge constraints of energy storage devices, space cooling constraints, heat gas and hot water demand constraints. However, both the two models [63,64] were simplified to single-objective optimization problems. Moreover, capacity constraints of energy storage devices and operation constraints of power generation units were not included.

Zoka et al. [65] studied the optimal operational issues of distributed generators and energy storage devices from the user perspective, and proposed an economic evaluation method for independent network of distributed generator resources. They also pointed out that the total cost of MG should include not only the installation and operating costs, but also self-construction cost and power interruption cost which are the measures of MG reliability. The total cost in the objective function is composed of operating costs, investment cost, and the revenue/costs of the transactions with main power grid. The operating costs consist of fuel costs and inspection and maintenance costs. The constraints in the model include power supply and demand balance constraint, heat supply and demand balance constraint, charge–discharge balance constraint of energy storage devices, generation capacity constraint, the constraints of other distributed generators, and non-negative constraints. The advantages of this model are twofold. First, its objective function integrates the concept of power interruption cost, which indicates the reliability of MG system. Second, the constitution of both its objective function and constraints is more comprehensive. However, the start-up costs and the line loss are ignored in the objective function. Also, energy storage capacity constraint is not included in the constraints.

In summary, all of the abovementioned MG optimal load distribution models were simplified to single-objective optimization problems. However, the optimal load distribution of MG is a multi-objective optimization problem in which we should not only consider the objective of costs, but also take the objectives of emissions, reliability, power line loss, power quality and power generation efficiency into account. These objectives are of great importance to the precise and effective optimal load distribution

of MG. Therefore, subjectively ignoring some of these objectives to simplify the multi-objective model into single-objective ones is unreasonable, which can directly affect the accuracy and effectiveness of the MG optimal load distribution results.

3.2. Multi-objective models

Mohamed and Koivo [66–69] studied the optimal modeling and online management of MG, and established a series of multi-objective nonlinear mathematical models of MG optimal load distribution, in which the minimizing of costs, emissions and the trade-off between them were considered at the same time. The operating costs of the multi-objective optimization model established in [66] are composed of fuel costs and operation and maintenance costs, while the start-up cost, revenue and costs with main power grid are not included.

The total emissions of pollutants in [66] are expressed as follows:

$$E(P_i)=\sum_{i=1}^{N}10^{-2}(\alpha_i+\beta_iP_i+\gamma_iP_i^2)+\zeta_i\exp(\lambda_iP_i) \tag{2}$$

where $E(P_i)$ is the emissions of unit i, $\alpha_i,\beta_i,\gamma_i,\zeta_i$ and λ_i are nonnegative coefficients describing the emission characteristics of the ith unit, and P_i is the real output of the ith unit.

The constraints in this model are inadequate, which only include the system power balance constraint and distributed generator operation constraint. Constraints of energy storage devices and system start-up time and quantity are not included. The incomplete model will lead to inaccurate results.

In [67], the authors analyzed the cost characteristics of wind power generation systems, photovoltaic systems, diesel generators, fuel cells, micro turbines, and batteries, and proposed the corresponding cost calculation methods. Then a multi-objective optimization model of MG was established. The emission objective function is the same as Eq. (2), while system start-up cost is added to the operating cost. However, some important factors, such as the revenue and costs with main power grid, are still not considered. For the constraints, the continuous running/stop time constraint and start-stop quantity constraint are added. But the charge-discharge constraint and capacity constraints are not taken into account.

The optimal load distribution model established in [68] is much more complete than the previous two models in [66,67]. The emission objective function is the same as Eq. (2), and operating costs include fuel cost, operation and maintenance cost, start-up cost, and the revenue and costs with main power grid. The operating costs function is presented as follows:

$$F(P_i)=\sum_{i=1}^{N}(C_iF_i+OM_i+SC_i+CPP_i-ISP_i) \tag{3}$$

where $F(P_i)$ is the total operating cost of unit i, P_i represents the actual power output of unit i, N is the total number of units in the MG system, C_i is the fuel costs of unit i, F_i is the fuel consumption rate of unit i, OM_i is the operation and maintenance cost of unit i, SC_i is the start-up cost of unit i, CPP_i is the cost of electricity purchased from the main power grid, and ISP_i is the income of electricity sales to the main power grid.

Constraints of the model in [68] are the same as those in [67], while the trading between MG and main power grid is considered more comprehensively. Two different conditions are considered to model the purchased and sold electricity.

$$CPP=C_p\times\max(P_L-P_i,0) \tag{4}$$

$$ISP=C_s\times\max(P_i-P_L,0) \tag{5}$$

where C_p and $C_s$are tariffs of the purchased and sold electricity respectively, P_i is the generated electricity, and P_L is the load demand.

In [69], the authors added the emission objective measured by emission factor to the total objective function. Operating cost and constraints are the same as those in [68]. This model also has some inadequacies. For example, the reliability, power line loss, power quality, and power efficiency are not considered in the objective function, and the charge–discharge constraint of energy storage devices is not included in the constraints of the model.

Wang et al. [70] studied the optimal management of distributed generation, and presented a multi-objective niche evolutionary immune algorithm (MO-NEIA). The objective function proposed includes electricity quality indicated by voltage deviation, operation efficiency of generators indicated by electricity factor, and power line loss. The constraints include variable constraints (active power, reactive power and voltage constraints), and power flow equation constraints. The main advantage of this model is that it takes the power quality, the operation efficiency of generators, and the power line loss into account, and the quantitative representations of these factors are given. These are rarely considered in other models. However, some costs are still not considered in their objective function, and system power balance constraint, charge–discharge and capacity constraint are not considered in constraint conditions.

Though multi-objective optimization models of MG optimal load distribution have been established in the aforementioned studies, the main objectives are still operating cost and emissions. Many important objectives, such as reliability, power line loss, power quality, power generation efficiency, etc., are still ignored. Meanwhile, the constraints are also inadequate.

Based on the review and analysis of existing studies on MG optimal load distribution, we find that many single- and multi-objective optimization models have been proposed. Some studies simplified the multi-objective optimization problem to single-objective one. Also some multi-objective models established were still inadequate in terms of objective functions and constraints. All of these problems will affect the precision and effectiveness of the optimal load distribution results of MG. Therefore, a more comprehensive model for MG optimal load distribution model is needed.

4. A comprehensive model of MG optimal load distribution

4.1. Objective function of MG optimal load distribution

Actually, the optimal load distribution of MG is a multi-objective optimization problem. Though the emission of MG is not so much as the traditional thermal power generation since renewable power generations are widely used in MG, we still cannot ignore the factor of emission in the objective function. In addition, a key characteristic of MG is its reliability which can be measured by the power interruption costs. Also, the electricity generated by MG is low voltage, so the power line loss cannot be ignored. Moreover, since transactions exist between MG and the main power grid when power generated by MG is not equal to the load demand, the revenue and cost of transactions between MG and the main power grid should be included in the total operating cost. Finally, power quality and operation efficiency of MG should also be considered. Therefore, the objective function of MG optimal load distribution is defined as follows:

$$\min F(P_i)=\min\{F_1(P_i),F_2(P_i),F_3(P_i),F_4(P_i),F_5(P_i),F_6(P_i)\} \tag{6}$$

$$F_1(P_i)=\sum_{i=1}^{N}(C_iF_i+M_i+S_i+CE_i+CP_i-CS_i) \tag{7}$$

$$F_2(P_i)=\sum_{i=1}^{N} E_i \tag{8}$$

$$F_3(P_i)=\sum_{i=1}^{N} R_i \tag{9}$$

$$F_4(P_i)=\sum_{i=1}^{N} L_i \tag{10}$$

$$F_5(P_i)=\sum_{i=1}^{N} Q_i \tag{11}$$

$$F_6(P_i)=\sum_{i=1}^{N} Eff_i \tag{12}$$

where $F(P_i)$ is the overall objective of MG system, $F_1(P_i)$ is the total operating costs, $F_2(P_i)$ is the total emissions, $F_3(P_i)$ is the interruption cost which indicates the reliability of MG, $F_4(P_i)$ is the total power line loss, $F_5(P_i)$ is the cost of maintaining an acceptable power quality, and$F_6(P_i)$ is the total power generation efficiency. In each of the objective function, P_i represents the actual power output from unit i in the MG system, N is the total number of units in MG, C_i is the fuel cost of unit i, F_i is the fuel consumption rate of unit i, M_i is the maintenance cost of unit i, S_i is the start-up cost of unit i, CE_i is the emission cost of unit i, CP_i is the cost of electricity purchased from the main power grid when the load demand exceeds the generated electricity from MG, CS_i is the income of electricity sold to the main power grid when the generated electricity from MG exceeds the load demand, E_i is the emission of unit i, R_i is the power interruption cost of unit i which indicates its reliability, L_i is the line loss of unit i, Q_i is the cost of maintaining an acceptable power quality of unit i, and Eff_i is the operation efficiency of unit i. For the distributed generators in MG, their operation efficiency "*Eff* " is the efficiency of converting the input energy into electrical energy. For the energy storage devices in MG, their "*Eff*" means the power output efficiency of the stored electrical energy. In general, the operation efficiency of MG refers to the total energy input-output efficiency.

See related references for the calculation of each optimization objective.

4.2. Constraints of MG optimal load distribution

4.2.1. Power supply and demand balance constraints

Power system balance constraints. The MG system should keep balance between power supply and demand. This equality constraint is denoted as follows:

$$\sum_{i=1}^{N} P_i+\sum_{i-1}^{Ns} ES_i+P_{purchase}-P_{sell}=P_L+L \tag{13}$$

where P_i is the actual output of unit i, ES_i is the stored energy of energy storage unit i, N andN_s are the total number of generators and energy storage devices respectively in the MG system,$P_{purchase}$ is electricity purchased from the main power grid, P_{sell} is the electricity sold to the main power grid, P_L is the total load, and $L$is the total power line loss.

Generation capacity constraints. The actual output of each unit should satisfy its lower and upper output limits as follows:

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{14}$$

where $P_i^{\min}$ are $P_i^{\max}$ are the lower and upper power out limits of unit i, respectively.

4.2.2. Operation constraints of energy storage devices

Charge-discharge constraints. Energy storage devices play important roles in MG, their operation must satisfy the charge–discharge constraints.

$$EC_i^{\min} \le EC_i \le EC_i^{\max} \tag{15}$$

$$ED_i^{\min} \le ED_i \le ED_i^{\max} \tag{16}$$

where EC_i and ED_i are charged and discharged amount of energy storage device i, respectively; $EC_i^{\min}$,$EC_i^{\max}$ and $ED_i^{\min}$,$ED_i^{\max}$ are the lower and upper limits of charge and discharge, respectively.

Capacity constraint. The capacity of energy storage devices must be in a certain interval range.

$$ES_i^{\min} \le ES_i \le ES_i^{\max} \tag{17}$$

where ES_i is the capacity of energy storage unit i, $ES_i^{\min}$ and $ES_i^{\max}$ are the corresponding lower and upper limits.

4.2.3. Power generation constraints of renewable energy

PV power constraint. The output of PV power is significantly affected by natural conditions, such as the temperature and the solar radiation at a certain time and in specific region. The PV power generated cannot exceed the power capacity under strongest nature condition.

$$P_{PV,i} \le P_{PV}^{\max} \tag{18}$$

where $P_{PV,i}$ is the power generated by PV unit i, and $P_{PV}^{\max}$ is its upper limit.

Wind power constraint. Wind velocity has a great impact on wind power generation. The wind power generation is limited as follows:

$$P_{WT,i} \le P_{WT}^{\max} \tag{19}$$

where $P_{WT,i}$ is the power generated by wind power unit i, and $P_{WT}^{\max}$ is its upper limit.

4.2.4. CHP system constraints

CHP power constraint. The power generated from CHP system cannot exceed the maximum value, which is expressed as follows:

$$P_{CHP,i} \le P_{CHP,i}^{\max} \tag{20}$$

where $P_{CHP,i}$ is the power generated from CHP unit i, and $P_{CHP,i}^{\max}$ is its upper limit.

Continuous running/stop time constraint. Once the units are switched on, they have to operate continuously for a certain minimum time before being switched off again. On the other hand, they have to maintain the termination status for a certain time before being started again. The violation of these constraints may shorten the life of the equipment [68]. The continuous running/stop time constraints are described as follows:

$$(T_{t-1,i}^{on}-MUT_i)(\theta_{t-1,i}-\theta_{t,i}) \ge 0 \tag{21}$$

$$(T_{t-1,i}^{off}-MDT_i)(\theta_{t-1,i}-\theta_{t,i}) \ge 0 \tag{22}$$

where $T_{t-1,i}^{on}/T_{t-1,i}^{off}$ is the on/off time of unit i, MUT_i and MDT_i are the minimum running and top time limits of unit i respectively, and $\theta_{t-1,i}$ represents the on/off status of unit i represented by 1/0.

Quantity constraint of start–stop units. The quantity of start and stop units cannot exceed a certain number.

$$N_{start-stop} \le N_{\max} \tag{23}$$

where $N_{start-stop}$ is the number of start-stop units, and $N_{\max}$ is the upper limit.

4.2.5. Other constraints

Reliability constraint. The failure of MG units will lead to the system outage. Taking the outage probability of MG into account,

the reliability constraint is defined as follows:

$$P_{ml} \leq \alpha P_L \tag{24}$$

where P_{ml} is the load that may loss, P_L is the total load, and α is the probability coefficient.

Emissions constraint. The distributed generators or energy storage devices that use fossil fuel will generate a certain amount of emissions. Emissions of MG must be limited in a certain interval range according to related environmental protection policies. Emissions constraint is expressed as follows:

$$\sum_{i=1}^{N} Y_{i,j} \leq Y_j^{\max} \tag{25}$$

where $Y_{i,j}$ is the amount of pollutant$j$ generated by unit i, and $Y_j^{\max}$ is the upper limit of pollutant j.

Voltage deviation constraint. The voltage deviation, which is typically a measure of power quality, of distributed generators and energy storage devices in MG cannot exceed an upper bound, which is described as follows:

$$\Delta V_i \leq \Delta V_{\max} \tag{26}$$

where ΔV_i is the voltage deviation of unit i, and $\Delta V_{\max}$ is the upper limit.

User defined constraints. In addition to the aforementioned various constraints. We should also note that emissions and efficiency in different equations may result in dependent rows in the array to solve. Therefore, in practical applications, this kind of user defined constraints should also be considered.

5. Conclusion

The optimal load distribution of MG is an important aspect to achieve its optimal operation and efficient application in the smart grid environment, and the establishment of optimization mathematical models is the first step of MG optimal load distribution. We first review some existing optimal load distribution models of MG, and pointed out the shortcomings of these models. Then we propose a general and comprehensive model. It is of great importance to improve the accuracy and effectiveness of MG optimal load distribution models, thereby promoting the study of MG economics and achieving the intelligent power generation and distribution of smart grid.

We should note that the selection of an appropriate MG optimal load distribution model in practical smart grid applications is important. The model established in this paper is a general model, and we should consider the specific characteristics while using the model. In addition, it is important to explore more effective and efficient algorithms to solve the optimal load distribution problems of MG after the model was established. Some of the traditional optimization methods [71–73] may not be suitable for MG optimal load distribution, which is a nonlinear, multi-objective and multi-constraint optimization problem. Some intelligent algorithms, such as genetic algorithms, bee colony optimization, and particle swarm optimization algorithm, are promising methods to solve the MG optimal load distribution problems [74–78].

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Nos. 71131002, 71071045 and 71201042) and the National High Technology Research and Development Program (863 Program) of China (No. 2011AA05A116).

References

[1] Schumacher EF. Small is beautiful: a study of economics as if people mattered. London, UK: Blond & Briggs; 1973.
[2] Lovins A. Small is profitable: the hidden economic benefits of making electrical resources the right size. Snowmass, CO, USA: Rocky Mountain Institute; 2002.
[3] Clark W, Isherwood W. Distributed generation: remote power systems with advanced storage technologies. Energy Policy 2004;32:1573–89.
[4] Ackermann T, Andersson G, Soder L. Distributed generation: a definition. Electr Power Syst Res 2001;57:195–204.
[5] Pepermans G, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W. Distributed generation: definition, benefits and issues. Energy Policy 2005;33:787–98.
[6] Chicco G, Mancarella P. Distributed multi-generation: a comprehensive view. Renew Sustainable Energy Rev 2009;13:535–51.
[7] Thornton A, Monroy CR. Distributed power generation in the United States. Renew Sustainable Energy Rev 2011;15:4809–17.
[8] Labis PE, Visande RG, Pallugna RC, Caliao ND. The contribution of renewable distributed generation in mitigating carbon dioxide emissions. Renew Sustainable Energy Rev 2011;15:4891–6.
[9] Borges CLT. An overview of reliability models and methods for distribution systems with renewable energy distributed generation. Renew Sustainable Energy Rev 2012;16:4008–15.
[10] Lasseter B. Microgrids. In: Proceedings of the 2001 IEEE power engineering society winter meeting; 2001. p. 146–49.
[11] Lasseter RH. Microgrids. In: Proceedings of the 2002 IEEE power engineering society winter meeting; 2002. p. 305–8.
[12] Huang J, Jiang C, Xu R. A review on distributed energy resources and MicroGrid. Renew Sustainable Energy Rev 2008;12:2472–83.
[13] Farhangi H. The path of the smart grid. IEEE Power Energy Mag 2010;8:18–28.
[14] Kanchev H, Lu D, Colas F, Lazarov V, Francois B. Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications. IEEE Trans Ind Electron 2011;58:4583–92.
[15] Molderink A, Bakker V, Bosman MG, Hurink JL, Smit GJ. Management and control of domestic smart grid technology. IEEE Trans Smart Grid 2010;1:109–19.
[16] Barnes M, Kondoh J, Asano H, et al. Real-world microgrids: an overview. In: Proceedings of the IEEE international conference on system of systems engineering; 2007. p. 1–8.
[17] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids. IEEE Power Energy Mag 2007;5:78–94.
[18] Dimeas AL, Hatziargyriou ND. Operation of a multiagent system for microgrid control. IEEE Trans Power Syst 2005;20:1447–55.
[19] Piagi P, Lasseter RH. Autonomous control of microgrids. In: Proceedings of the IEEE power engineering society general meeting; 2006. p. 8–15.
[20] Wang CS, Xiao ZX, Wang SX. Synthetical control and analysis of microgrid. Autom Electr Power Syst 2008;32:98–103.
[21] Lopes PJA, Moreira CL, Madureira AG. Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 2006;21:916–24.
[22] Chen C, Duan S, Cai T, Liu B, Hu G. Smart energy management system for optimal microgrid economic operation. IET Renew Power Gener 2011;5:258–67.
[23] Venkataramanan G, Marnay C. A larger role for microgrids. IEEE Power Energy Mag 2008;6:78–82.
[24] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrids management. IEEE Power Energy Mag 2008;6:54–65.
[25] Asanol H, Bandol S. Economic analysis of microgrids. In: Proceedings of the power conversion conference; 2007. p. 654–58.
[26] Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based supply system for microgrids. Renew Energy 2012;45:7–15.
[27] Zhou KL, Yang SL, Shen C. A review of electric load classification in smart grid environment. Renew Sustainable Energy Rev 2013;24:103–10.
[28] Zhou KL, Yang SL. An improved fuzzy C-Means algorithm for power load characteristics classification. Power Syst Prot Control 2012;40:58–63.
[29] Asano H, Bando S. Economic evaluation of microgrids. In: Proceedings of IEEE power and energy society general meeting; 2008. p. 6.
[30] Zoka Y, Koeda K, Sugimoto A. et al. An economic evaluation for an autonomous independent network of distributed generators. In: Proceedings of the 7th international power engineering conference; 2005. p. 657–62.
[31] Costa PM, Matos MA. Economic analysis of microgrids including reliability aspects. In: Proceedings of the IEEE international conference on probabilistic methods applied to power systems; 2006. p. 1–8.
[32] Gu W, Wu Z, Yuan X. Microgrid economic optimal operation of the combined heat and power system with renewable energy. In: Proceedings of the IEEE power and energy society general meeting; 2010. p. 1–6.
[33] Griffin T, Tomsovic K, Secrest D, Law A. Placement of dispersed generation systems for reduced losses. In: Proceedings of the 33rd annual Hawaii international conference on system sciences; 2000. p. 1–9.
[34] Keane A, O'Malley M. Optimal allocation of embedded generation on distribution networks. IEEE Trans Power Syst 2005;20:1640–6.
[35] Caisheng W, Nehrir MH. Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Trans Power Syst 2004;19:2068–76.
[36] AlHajri MF, El-Hawary ME. Optimal distribution generation sizing via fast sequential quadratic programming. In: Proceedings of the large engineering systems conference on power engineering; 2007. p. 63–6.

[37] Khoa TQD, Binh PTT, Tran HB. Optimizing location and sizing of distributed generation in distribution systems. In: Proceedings of the IEEE PES power systems conference and exposition; 2006. p. 725–32.
[38] Celli G, Ghiani E, Mocci S, Pilo F. A multiobjective evolutionary algorithm for the sizing and sitting of distributed generation. IEEE Trans Power Syst 2005;20:750–7.
[39] Morais H, Kádár P, Faria P, Vale ZA, Khodr HM. Optimal scheduling of a renewable micro-grid in an isolated load area using mixed-integer linear programming. Renew Energy 2010;35:151–6.
[40] Clamart, France: EPRI; 2006.
[41] Paul H. IntelliGrid: a smart network of power. EPRI J 2005:17–25.
[42] Fang X, Misra S, Xue G, Yang D. Smart grid—the new and improved power grid: a survey. IEEE Commun Surv Tutor 2012;14:944–80.
[43] Fadaeenejad M, Saberian AM, Fadaee M. The present and future of smart power grid in developing countries. Renew Sustainable Energy Rev 2014;29:828–34.
[44] Colak I, Bayindir R, Fulli G, Tekin I, Demirtas K, Covrig CF. Smart grid opportunities and applications in Turkey. Renew Sustainable Energy Rev 2014;33:344–52.
[45] Wu YN, Chen J, Liu LR. Construction of China's smart grid information system analysis. Renew Sustainable Energy Rev 2011;15:4236–41.
[46] Massoud AS, Wollenberg BF. Toward a smart grid: power delivery for the 21st century. IEEE Power Energy Mag 2005;3:34–41.
[47] Chen SY, Song SF, Li L, Shen J. Suvery on smart grid technology. J Power Syst Technol 2009;33:1–7.
[48] Moslehi K, Kumar R. A reliability perspective of the smart grid. IEEE Trans Smart Grid 2010;1:57–64.
[49] Zhang XP. A framework for operation and control of smart grids with distributed generation. In: Proceedings of the power and energy society general meeting-conversion and delivery of electrical energy in the 21st century; 2008. p. 1–5.
[50] Mohd A, Ortjohann E, Schmelter A, Hamsic N, Morton D. Challenges in integrating distributed energy storage systems into future smart grid. In: Proceedings of the IEEE international symposium on industrial electronics; 2008. p. 1627–32.
[51] Chowdhury SP, Chowdhury S, Ten CF, Crossley PA. Operation and control of DG based power island in smart grid environment. In: Proceedings of the international conference and exhibition on electricity distribution; 2009. p. 1–5.
[52] Katiraei F, Iravani MR. Power management strategies for a microgrid with multiple distributed generation units. IEEE Trans Power Syst 2006;21: 1821–31.
[53] Lu ZX, Wang CX, Min Y. Overview on microgrid research. Autom Electr Power Syst 2007;31:100–7.
[54] CERTS. Distributed energy resources integration. Available from: 〈http://certs.lbl.gov/certs-der.html〉.
[55] Masoum MA, Dehbonei H, Fuchs EF. Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking. IEEE Trans Energy Convers 2002;17:514–22.
[56] Kuo YC, Liang TJ, Chen JF. Novel maximum-power-point-tracking controller for photovoltaic energy conversion system. IEEE Trans Ind Electron 2001;48: 594–601.
[57] Li P. Condition for equal incremental principle application to unit load optimizing distribution. South Power Syst Technol 2008;2:43–6.
[58] Chen DW, Zhu GP. An investigation on optimal load distribution of microgrids. Autom Electr Power Syst 2010;34:45–9.
[59] Farag A, Al-Baiyat S, Cheng TC. Economic load dispatch multiobjective optimization procedure using linear programming techniques. IEEE Trans Power Syst 1995;10:731–8.
[60] Abido MA. Environmental/economic power dispatch using multiobjective evolutionary algorithms. IEEE Trans Power Syst 2003;18:1529–37.
[61] Nanda J, Kothari DP, Lingamurthy KS. Economic-emission load dispatch through goal programming techniques. IEEE Trans Power Syst 1988;3:26–32.
[62] Hernandez-Aramburo CA, Green TC, Mugniot N. Fuel consumption minimization of a microgrid. IEEE Trans Ind Appl 2005;41:673–81.
[63] Asanol H, Bandol S. Economic analysis of microgrids. In: Proceedings of the power conversion conference; 2007. p. 654–8.
[64] Asano H, Bando S. Economic evaluation of microgrids. In: Proceedings of the power and energy society general meeting-conversion and delivery of electrical energy in the 21st Century; 2007. p. 1–6.
[65] Zoka Y, Sugimoto A, Yorino N, Kawahara K, Kubokawa J. An economic evaluation for an autonomous independent network of distributed energy resources. Electr Power Syst Res 2007;77:831–8.
[66] Mohamed FA, Koivo HN. System modelling and online optimal management of microgrid using multiobjective optimization. In: Proceedings of the international conference on clean electrical power; 2007, p. 148–53.
[67] Mohamed FA, Koivo HN. Online management of microgrid with battery storage using multiobjective optimization. In: Proceedings of the international conference on power engineering, energy and electrical drives; 2007. p. 231–6.
[68] Mohamed FA, Koivo HN. MicroGrid online management and balancing using multiobjective optimization. IEEE Lausanne Power Tech 2007:639–44.
[69] Mohamed FA, Koivo HN. System modelling and online optimal management of microgrid using mesh adaptive direct search. Int J Electr Power Energy Syst 2010;32:398–407.
[70] Wang XG, Ai Q, Xu WH, Han P. Multi-objective optimal energy management of microgrid with distributed generation. Power Syst Prot Control 2009;37:79–83.
[71] Kavrakoğlu I, Kiziltan G. Multiobjective strategies in power systems planning. Eur J Oper Res 1983;12:159–70.
[72] Makkonen S, Lahdelma R. Non-convex power plant modelling in energy optimization. Eur J Oper Res 2006;171:1113–26.
[73] Nowak M P, Romisch W. Stochastic Lagrangian relaxation applied to power scheduling in a hydro-thermal system under uncertainty. Ann Oper Res 2000;100:251–72.
[74] Zhou KL, Shen C, Ding S, Yang SL. Power economic dispatch of microgrid based on genetic algorithm. Chin J Manag Sci 2014;22:68–73.
[75] Li F. A comparison of genetic algorithms with conventional techniques on aspectrum of powere conomic dispatch problems. Expert Syst Appl 1998;15:133–42.
[76] Basu M. Bee colony optimization for combined heat and power economic dispatch. Expert Syst Appl 2011;38:13527–31.
[77] Li X, Niu DX, Yang SD. Application of the improved particle swarm optimization algorithm in the generation expansion planning. Chin J Manag Sci 2006;14:113–8.
[78] Xu LZ, Yang GY, Xu Z, Bao ZJ, Jiang QY, Cao YJ, et al. A co-ordinated dispatch model for electricity and heat in a microgrid via particle swarm optimization. Trans Inst Meas Control 2013;35:44–55.